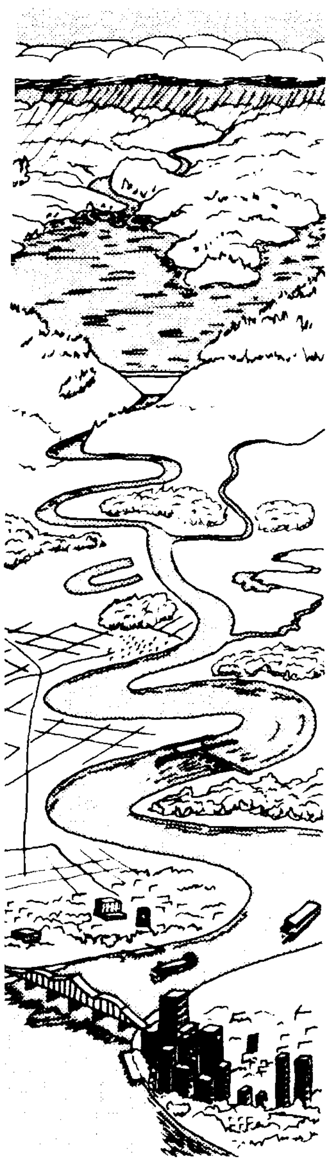
US Army Corps of Engineers



WATER QUALITY RESEARCH PROGRAM

MISCELLANEOUS PAPER W-92-2

DESTRATIFICATION SYSTEM DESIGN FOR EAST SIDNEY LAKE, NEW YORK

by

Edward B. Meyer, Richard E. Price, Steven C. Wilhelms

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

September 1992
Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under WQRP Work Unit 32514

Monitored by Environmental Laboratory
US Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

ENVIRONMENTAL LABORATORY

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1992

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Destratification System Design for East Sidney Lake, New York

5. FUNDING NUMBERS
WU 32514

6. AUTHOR(S)
Edward B. Meyer
Richard E. Price
Steven C. Wilhelms

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station, Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers, Washington, DC 20314-1000

USAE Waterways Experiment Station, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Miscellaneous Paper W-92-2

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Reservoir destratification was applied to East Sidney Reservoir, New York, to fulfill objectives of a general research effort and to solve the specific problems encountered at East Sidney. The study was conducted to (a) gain general experience in the design, construction, and installation of a pneumatic destratification system; (b) evaluate system performance and design methods; and (c) develop methods for operational control of a destratification system. The initial design of the destratification system included a large degree of flexibility to permit evaluation of alternative operations. The initial configuration of the destratification system, which is the subject of this report, consisted of a diffuser longer than required by the design criteria under evaluation. System performance was evaluated relative to its effectiveness at eliminating and preventing thermal stratification. Tests were conducted in 1989 to assess the local mixing characteristics of the system and in 1990 to assess the full-lake effects of system operation. Also in 1990, the
(Continued)

14. SUBJECT TERMS
Destratification, Reservoir, Pneumatic, Stratification

15. NUMBER OF PAGES
43

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. ABSTRACT (Continued).

daily duration of system operation was varied depending upon the degree of lake stratification to develop guidance for operation and verify the applicability of an in-lake monitoring system for controlling the destratification system.

PREFACE

The work reported herein was conducted as part of the Water Quality Research Program (WQRP), Work Unit 32514. The WQRP is sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE), and is assigned to the US Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation 96X3121, "General Investigation." The WQRP is managed under the Environmental Resources Research and Assistance Programs (ERRAP), Mr. J. L. Decell, Manager. Mr. Robert C. Gunkel was Assistant Manager, ERRAP, for the WQRP. Technical Monitors during this study were Messrs. Pete Juhle and Jim Gottesman and Dr. John Bushman, HQUSACE.

The investigation of the destratification system for East Sidney Lake, New York, reported herein, was conducted by the Hydraulics Laboratory (HL), WES. The effort was jointly funded by the US Army Engineer District, Baltimore (NAB), and the WQRP under Work Unit 32514, "Field Evaluation of Mixers and Aerators," as a demonstration of technology developed under the WQRP.

The investigation was conducted during the period January 1989 to March 1991 under the direction of Messrs. F. A. Herrmann, Jr., Chief, HL; R. A. Sager, Assistant Chief, HL; G. A. Pickering, Chief, Hydraulic Structures Division (HSD), HL; and under the direct supervision of Dr. J. P. Holland, Chief, Reservoir Water Quality Branch (RWQB), HSD. This report was prepared by CPT E. B. Meyer, Dr. R. E. Price, and Mr. S. C. Wilhelms, RWQB. Mr. Calvin Buie and Ms. Laurin Yates, RWQB, assisted in field testing and data analysis, respectively. Peer review was performed by Mr. C. W. Downer, RWQB. The report was edited by Mrs. M. C. Gay, Information Technology Laboratory, WES.

Dr. Robert W. Whalin was Director of WES. COL Leonard G. Hassell, EN, was Commander and Deputy Director.

This report should be cited as follows:

> Meyer, Edward B., Price, Richard E., and Wilhelms, Steven C. 1992. "Destratification System Design for East Sidney Lake, New York," Miscellaneous Paper W-92-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acre-feet	1,233.489	cubic metres
acres	4,046.873	square metres
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
horsepower (550 ft-pounds (force) per second)	745.6999	watts
inches	2.54	centimetres
pounds (force) per square inch	6.894757	kilopascals
square miles	2.589998	square kilometres

DESTRATIFICATION SYSTEM DESIGN FOR EAST SIDNEY LAKE, NEW YORK

PART I: INTRODUCTION

Project Description

1. East Sidney Lake is a small flood control impoundment located in Delaware County on Ouleout Creek, a tributary of the Unadilla River in central New York State. It was completed in 1950 to provide flood control on part of the north branch of the Susquehanna River basin (Figure 1). This project, operated by the US Army Engineer District, Baltimore, impounds 3,350 acre-ft* of water with a surface area of 210 acres at a summer pool elevation of 1150.** Under flood conditions the lake impounds 33,550 acre-ft at a spillway crest elevation of 1203. The drainage area of the stream above the dam is 102 square miles. During the summer the average depth of the reservoir is approximately 16 ft, with a maximum depth of 50 ft just upstream of the dam.

2. The dam is a combination concrete and earthen structure. The concrete structure contains the uncontrolled spillway (crest length of 240 ft) and five gated conduits to pass normal and flood flows. The conduits are 3.5 ft wide by 5.83 ft high with intake center-line elevations of 1117.9. In addition to providing flood control, the project is also a significant recreation facility for the area with a locally operated recreation area on the reservoir just upstream of the dam. This area provides facilities for seasonal camping, picnicking, boating, and supervised swimming areas. The project also includes 1,267 acres of wooded and semiwooded land surrounding the lake as part of the flood control pool.

3. In general, the water quality of East Sidney Lake is typical of lakes in this region: it stratifies thermally and chemically during the summer season. Because of solar input to the lake surface and warm inflows, the lake stratifies with warmer water in a surface region (epilimnion) and cooler water near the lake bottom (hypolimnion). The thermal stratification prevents

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

** All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

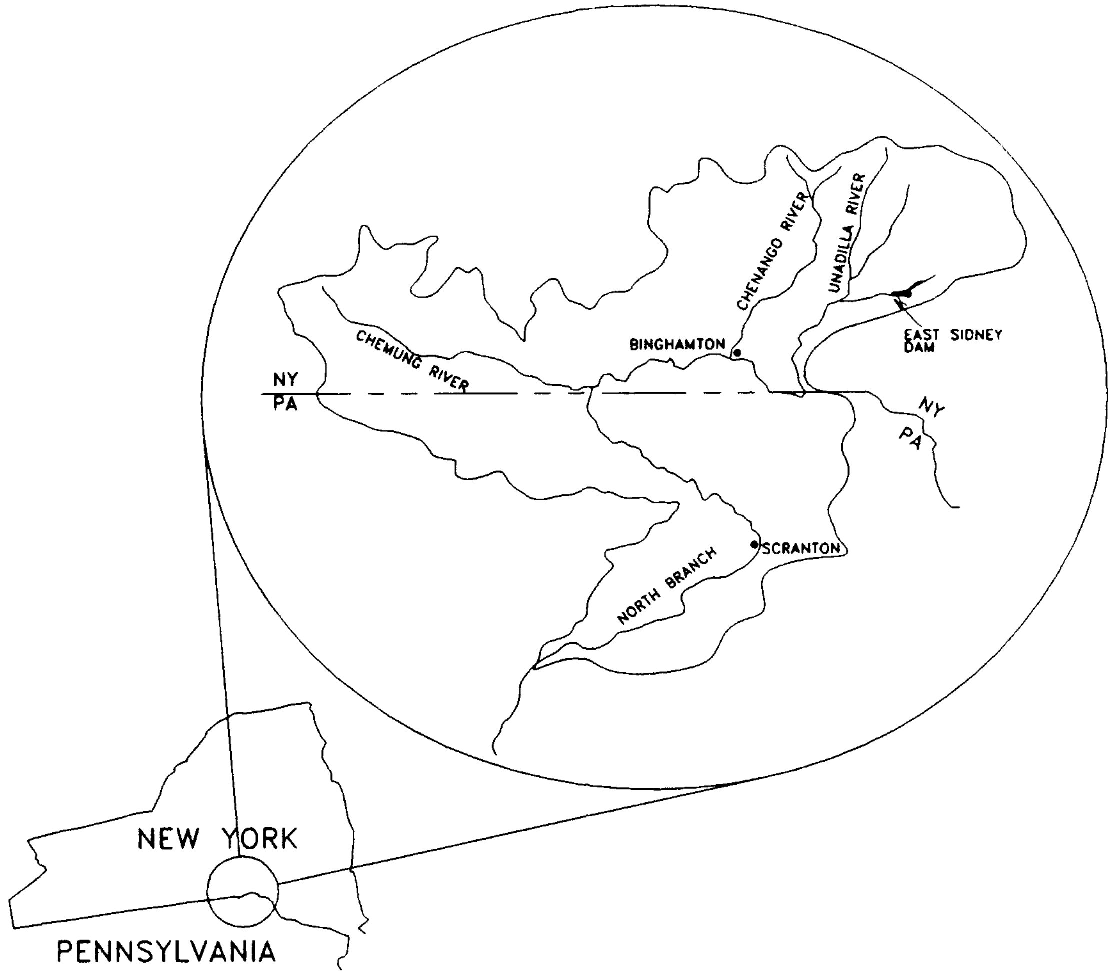


Figure 1. Location map for East Sidney Lake

the transport of oxygen from the atmosphere to the depths of the lake. Thus, water near the bottom often becomes anoxic. During the summer months, algal blooms may occur and create water quality problems. The two main sources of nutrients for these blooms are the runoff from within the watershed during storm events and internal loading (Kennedy et al. 1988) through recycling from lake sediments during stratification. Control of nonpoint source nutrient loading may be accomplished through control of activities within the watershed. This typically will involve a local soil conservation agency and may be beyond the authority of the project manager. Control of nutrient recycling within the reservoir, however, may be possible through reservoir water quality enhancement techniques such as destratification.

4. The thermal stratification at East Sidney Lake during the summer months may be described as relatively weak, although the chemical

stratification that results from the thermal stratification can be significant. Stratification of the lake, which generally begins in mid-April to late April, strengthens as the summer progresses. Due to the withdrawal characteristics of the outlet works at the dam, the lake is prevented from developing a strong stratification. The gates used to regulate the discharge are located near the bottom in the deepest portion of the lake. As a result, water is withdrawn primarily from the lower elevations of the lake. As the summer progresses, the colder hypolimnetic water is continually removed and replaced by warmer water from higher in the water column, weakening the thermal stratification. Nevertheless, the hypolimnetic water may become anoxic and nutrients can become chemically reduced. Upon chemical or physical resuspension in the water column, they may then be made available for uptake by algae.

5. Reservoir destratification is a technique typically used to enhance overall lake water quality when the problems can be characterized such as those at East Sidney. Water from the lower levels of the reservoir is prevented from becoming anoxic through a combination of mixing with epilimnetic water, exposure to the water surface for oxygen absorption, and reoxygenation from the rising bubble plume, if a pneumatic destratification system is used. This technique seems particularly suited to East Sidney Lake due to the relatively small size of the reservoir and the weak thermal stratification.

Objectives and Scope

6. The purposes of this study were rooted in applied research and solution of a specific problem. It was conducted to (a) gain general experience in the design, construction, and installation of a pneumatic destratification system; (b) evaluate system performance and design methods; and (c) develop methods for operational control of a destratification system. The initial design, discussed in the following section, was modified to provide a large degree of flexibility in operation. This flexibility was included to permit evaluation of alternative operations in subsequent research studies. The initial configuration of the destratification system, which is the subject of this report, consisted of a diffuser longer than required by Davis' (1980) design criteria. Additional testing of the system will be conducted to assess alternative design points and operations. System performance was evaluated relative to its effectiveness at eliminating and preventing thermal

stratification. Tests were conducted in 1989 to assess the local mixing characteristics of the system and in 1990 to assess the full-lake effects of system operation. Also in 1990, the daily duration of system operation was varied depending upon the degree of lake stratification to develop guidance for operation and verify the applicability of an in-lake monitoring system for controlling the destratification system.

PART II: DESTRATIFICATION SYSTEM DESIGN

Destratification Concepts

7. Destratification is based on artificially mixing of a reservoir to establish and maintain relatively uniform temperature profiles in the reservoir. One way to accomplish this is to introduce a source of air bubbles at the lake bottom. The rising bubbles induce a circulation pattern by entraining water as the bubble plume rises. This entrained water rises to the surface and then moves out laterally. Additional water moves in to replace the upward flow and a circulation and mixing cell is created (Figure 2). The size and volume of these cells are usually determined by the physical boundaries of the reservoir and the strength of the flow induced by the rising bubble plume.

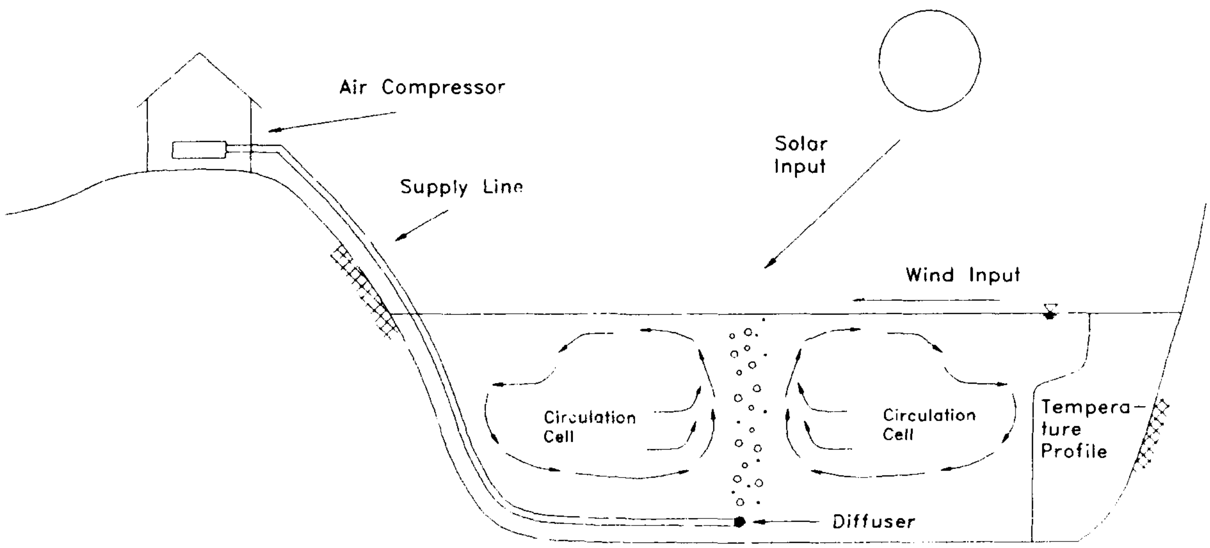


Figure 2. Circulation pattern generated by a bubble plume

8. A number of theoretical investigations and laboratory experiments have been conducted to determine the flow patterns for destratification processes. Asaeda and Imberger (1988) have investigated the effects of a rising bubble plume on different types of stratification patterns (linear and two-layer). They identified a "bubble plume number" to characterize the effects on the destratification process. Kararenburg (1979), Gossens (1979), and Zic, Stefan, and Ellis (in preparation) verified the formation of an interflow in the intermediate (thermocline) region during the destratification process. Zic and Stefan (1990) and Patterson and Imberger (1989) developed numerical

models of this process to identify near-field (in the vicinity of the rising bubble plume) impacts and far-field (in the remainder of the lake at a distance from the mixing cell) impacts and to simulate the destratification process in reservoirs.

Design Procedure

9. Johnson (1984) provides an overview of the various types of pneumatic destratification systems in use and how they operate. He also provides guidelines for system selection based upon the lake characteristics and the goals of the system to be installed. The pneumatic system must input enough energy into the reservoir to overcome the stability created by density stratification, which is usually a consequence of thermal stratification, and thereby mix the region of interest resulting in an unstratified condition. In general, destratification system design is based on the volume of water to be fully mixed, a representative temperature profile, and the desired time to destratify the lake.

10. Davis (1980) presents the basis and guidelines to design a destratification system. The system designed with this procedure relies on a single, linear perforated pipe to deliver air bubbles that rise through the water column and induce vertical mixing. Davis outlined the following procedure for sizing a destratification system:

- a. The first step in Davis' design process is the estimation of stability* of the reservoir under a particular stratification. For a given temperature profile and reservoir bathymetry, the stability of the volume to be destratified is determined from the potential energy of the mixed (homogeneous) reservoir minus the potential energy of the stratified reservoir.
- b. The energy determined would be required to destratify the reservoir if there were no additional input from the sun or mixing induced by wind. However, solar and wind energy will affect the energy required. Therefore, Davis provides a means to estimate required energy based on a combination of the stability and the solar and wind energy input to the reservoir.
- c. In Davis' procedure, the flow rate of air required to destratify the reservoir is then determined based on the total required energy, the desired time to destratify the reservoir

---

* Stability is defined as a minimum theoretical energy required to mix the reservoir from an initially stratified state to an isothermal state (Symons 1969).

volume, and the depth of water above the diffuser. Davis recommends a minimum airflow of 42 standard cubic feet per minute (scfm) (20 ℓ/s).

d. A diffuser system that can accommodate the required airflow rate is then sized based on the volume, depth, airflow, and time to destratify. This diffuser system consists of a linear piping system perforated with 0.0394-in.-diameter holes located 12 in. on center. Davis recommends that the minimum length of perforated pipe be 164 ft.

e. The compressor must be able to provide the required airflow at a pressure sufficient to overcome the hydrostatic head and the losses through the air supply system. This pressure must account for the hydrostatic pressure head, pressure loss due to friction and bends in the pipe, and excess pressure at the end of the pipe.

f. The free airflow through a single diffuser hole is determined using the ratio of absolute hydraulic pressure (pressure due to the water depth and atmospheric pressure) to the mean internal absolute pressure (pressure at the end of the diffuser pipe plus the absolute hydraulic pressure). This value is multiplied by the number of holes in the diffuser pipe and compared to the airflow required. If it is not equal to or greater than the airflow, the length of pipe is increased and the pressure requirements are recalculated. Several iterations through the pressure and length calculations may be required to arrive at a satisfactory solution.

g. An anchoring system that is capable of submerging the diffuser pipe is the final component that must be designed.

11. According to the Davis criteria, the system should be activated at the beginning of the stratification period before the temperature difference from surface to bottom exceeds 4 °C or when the oxygen content of the hypolimnion falls to 50 percent of the saturation level. Operation should continue until the temperature difference from surface to bottom is less than 2 °C or the dissolved oxygen reaches a suitable level. Once the initial destratification is accomplished, the system may be operated intermittently throughout the remainder of the season when thermal or oxygen stratification reaches an undesirable level.

East Sidney System Design

12. Davis' design procedure is presented in a series of nomographs and in a set of equations. The choice of using the nomographs or the equations depends upon the availability of temperature profile data from the reservoir.

If very little data exist for a reservoir, the nomographs in Davis' text provide guidance for a general reservoir system and a typical temperature profile with a 4° C surface-to-bottom difference. In lieu of specific temperature profiles, these generalized graphs can be used to design a destratification system, as follows:

- a. Based upon the depth of the reservoir and volume to be destratified, an approximate stability can be estimated from a graph.
- b. Using this stability and approximating the effects of solar input and wind mixing, the approximate energy required to destratify the volume in 5 days can be calculated.
- c. With this energy estimate and the depth, the airflow rate can be determined from Davis' nomographs.
- d. In turn, the length of diffuser pipe and compressor requirements can be estimated from nomographs.

The second method is to calculate all of the system requirements using Davis' formulas and specific data from the reservoir. These results are geared specifically toward the temperature profile and bathymetry of the reservoir. This requires detailed information on thermal profiles over time, but produces a system better suited for the particular reservoir. Meyer (1991) reports on a spreadsheet computer program that performs these calculations.

13. The nomographic method was used to develop the original design for East Sidney Lake. Subsequent to the installation and testing of the system, the calculational procedure (Meyer 1991) was developed. For comparison in this report, both methods were used to design a system for East Sidney Lake. Results are shown in Table 1. Specifically, for system design purposes, the following was used: (a) time to destratify the reservoir 5 days, (b) initial surface-to-bottom temperature difference assumed at 4 °C, and (c) residual thermal stratification from surface to bottom of 2 °C or less after

Table 1

Comparison of Calculated and Graphical Design (Davis 1980) of Pneumatic Destratification System for East Sidney Lake

Solution Type	Solar Energy mj	Total Energy mj	Airflow scfm	Pressure psig	Diffuser Length ft
Graphical	21.45	35.50	54.08	47.75	351
Calculated	21.45	54.12	77.22	54.53	443

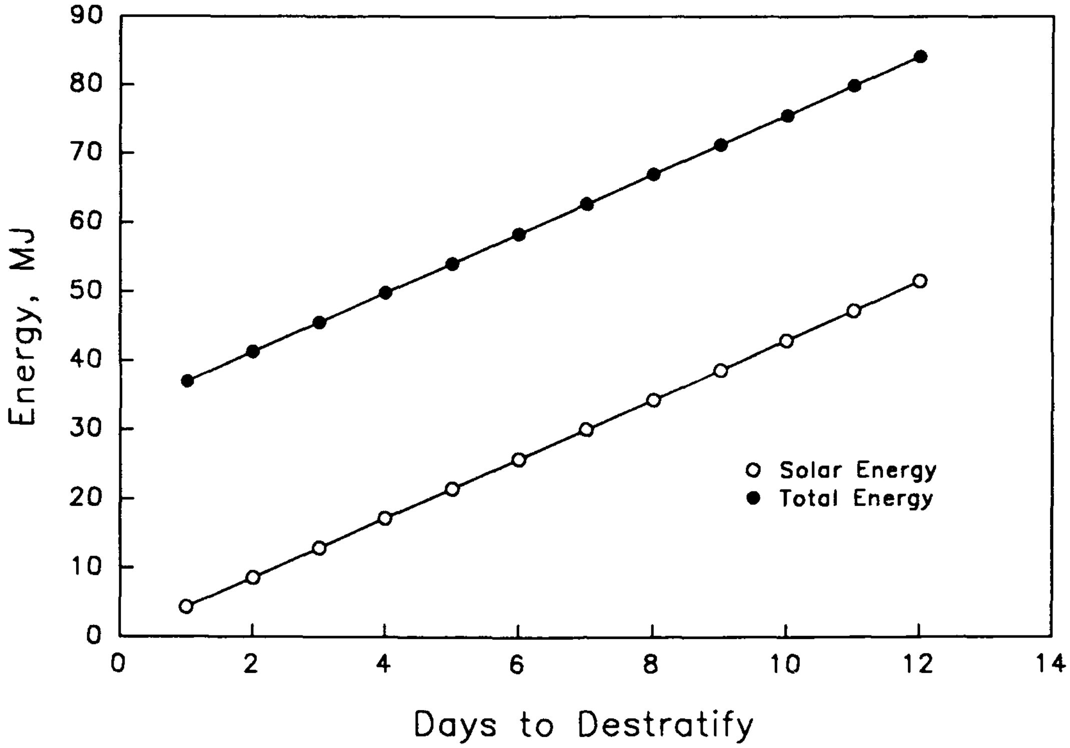
destratification. The total energy derived from Davis' graphical procedure was less than that from the calculated method, resulting in a lower airflow rate and smaller compressor size.

14. The period of time required to destratify the lake is an important parameter in the design process, because a shorter desired destratification time requires more rapid mixing. Thus, the size of the destratification system is highly dependent upon the time in which the lake is to be destratified. Using Davis' (1980) formulations, Figure 3 shows the relationships between time to destratify the lake and system requirements calculated for the same temperature profile of 4 °C (12 °C surface and 8 °C bottom) temperature change through the thermocline. As indicated, a large system would be required to destratify even a lake as small as East Sidney in 1 or 2 days. A reasonably sized system would destratify the lake in approximately 4 to 6 days. It appears to be possible to design a small system to destratify the reservoir over an extended period of time (more than 6 days), but because of the solar input to the lake, the possibility exists that the stratification could become so strong that the effect of the small system would be marginal or negligible.

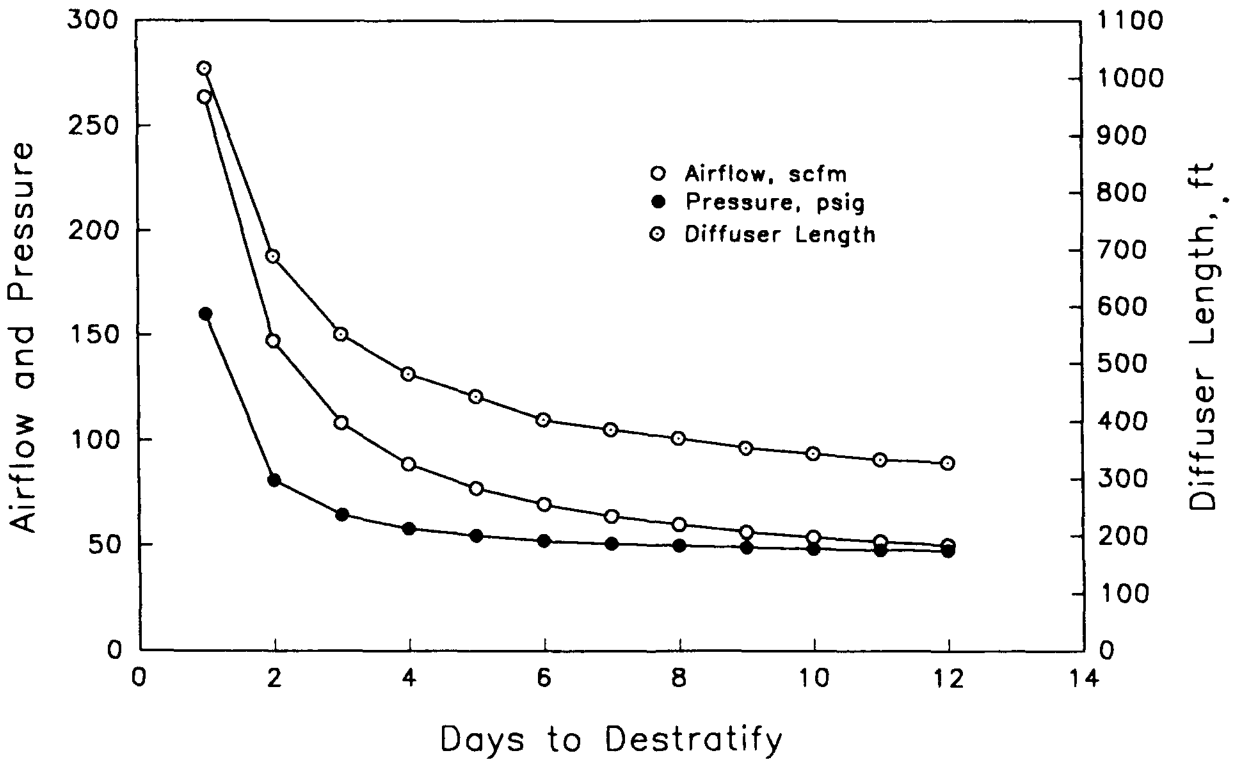
15. The specific design parameters for the destratification system at East Sidney Lake are listed in Table 2. Based on estimates from compressor manufacturers, a 15-hp compressor was selected to provide the airflow and pressure required by the design. The diffuser length computed from the design procedure was 351 ft. However, to provide additional operational control and a large degree of flexibility, the diffuser length was increased to 800 ft. The diffuser was designed to be a continuous length of 1-1/2-in. polyvinyl chloride (PVC) schedule 80 pipe. Although the pipe was joined as one continuous length, each 100-ft section was sealed from the adjoining section by a PVC plug. Airflow was controlled through a manifold and valve system to each 100-ft section to allow variation of diffuser length from 100 to 800 ft.

System Fabrication and Installation

16. Much of the system was prefabricated in a shop. The diffuser pipe, purchased as 20-ft-long sections of schedule 80 PVC pipe, was drilled with a 0.0394-in.-diameter drill bit producing holes approximately 0.031 in. in diameter every 12 in. Connections for air supply lines were installed on each



a. Energy required to destratify as a function of destratification time



b. Airflow, delivery pressure, and diffuser length as a function of destratification time

Figure 3. Relationships between time to destratify the lake and system requirements calculated for 4 °C

Table 2

Destratification System Specifications

Oilless Compressor	15 hp	64 scfm @ 50 psi 52.4 scfm @ 100 psi
Main supply line (land)	380 ft	2-in. galvanized pipe
Main supply line (water)	1,000 ft	1-1/2-in. flexible rubber hose
Feeder lines	1,600 ft	3/4-in. flexible rubber hose
Diffuser	800 ft	Schedule 80 PVC pipe
Manifold	8 valves	Schedule 80 PVC supply valves

100-ft-long section. A manifold for distribution and control of airflow to the diffuser sections was also constructed. The diffuser pipes, manifold, and supply line were transported to East Sidney Lake for final assembly and installation.

17. The compressor was located in a small shed on the top of the earthen portion of the dam near the concrete structure (Figure 4). This location provided easy access for construction, maintenance, and electrical power and was reasonably secure from intruders and safe from flooding. The air supply line from the compressor to the water's edge was a 2-in.-diameter galvanized steel pipe. The use of steel pipe is advised to dissipate heat generated by compression of the air. (The air exiting the compressor is extremely hot, on the order of 60-70 °C, and should be cooled before entering the lake to prevent artificial warming.) The galvanized pipe was installed on the ground surface on top of the riprap from the compressor shed to the toe of the dam (a distance of approximately 140 ft). It was then buried about 3 ft underground parallel to the dam face to the edge of the water (a distance of approximately 240 ft).

18. The galvanized pipe was connected to a 1.5-in.-diameter flexible supply hose near the lake shore. The flexible hose was buried from this connection with the galvanized pipe (approximately 10 ft from the water's edge) to about 15 ft into the lake. Burying the hose where it entered the water

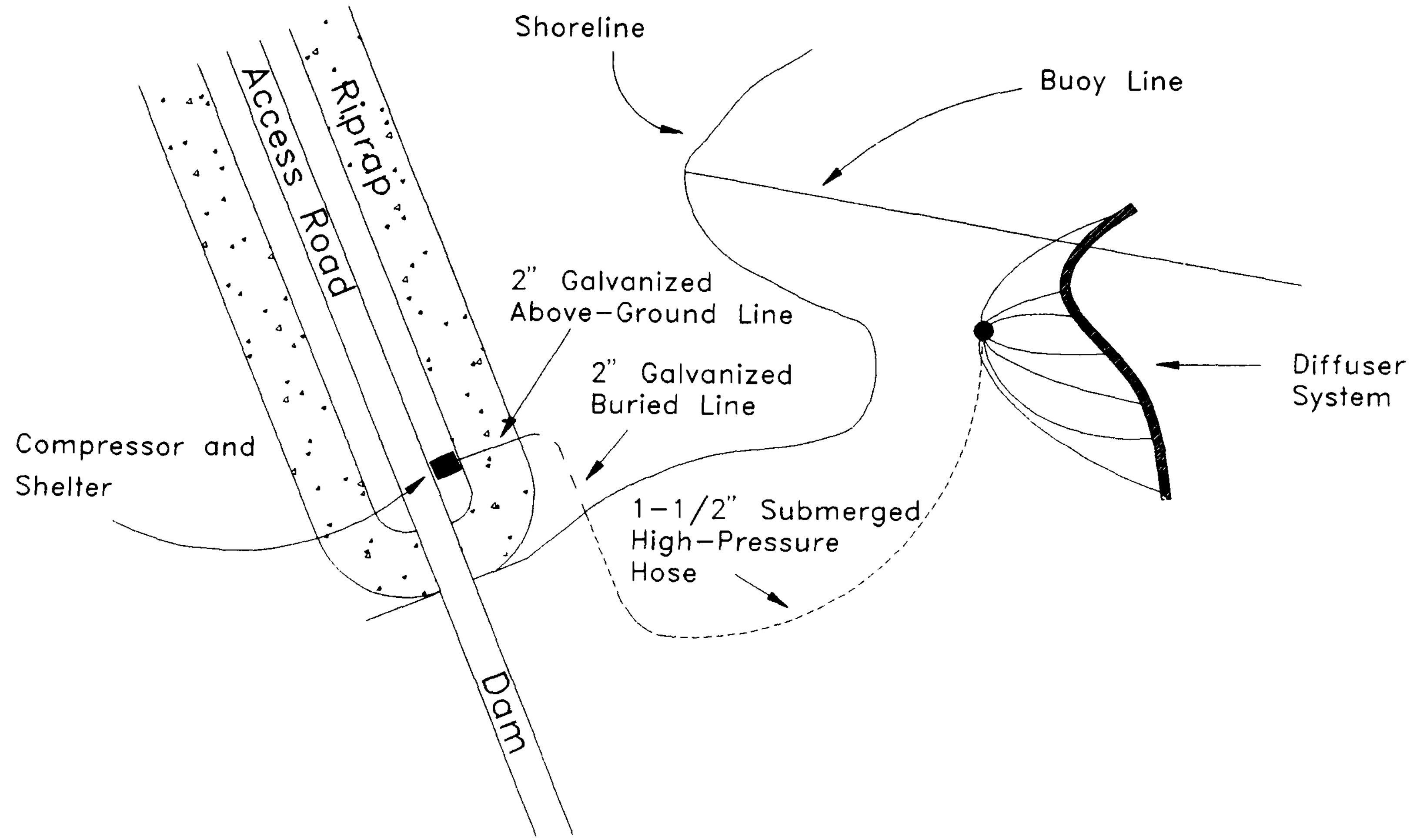


Figure 4. Compressor enclosure and supply lines

provided protection from ice forces during the winter. The hose was weighted with bricks (one brick every 4 ft) to keep it submerged along the bottom of the lake.

19. The diffuser manifold consisted of eight valves that provided air-flow regulation to the eight 100-ft diffuser sections. This provided some flexibility in operating the diffusers for testing purposes and in isolating sections should problems arise. From the manifold, air was supplied to each 100-ft-long diffuser section through 3/4-in.-diameter flexible hosing feeder lines.

20. The 100-ft-long sections of diffuser were assembled onsite from the 20-ft-long PVC pipe sections. The entire diffuser system was floated to the thalweg of the Unadilla River approximately 1,200 ft upstream of the dam. Bricks were used for ballast and the diffuser was sunk in the deepest location in the lake.

21. Three air pressure gages were installed in the system to monitor its operation. Gages were installed at the compressor, manifold, and at the end of one of the diffuser lengths. These allowed monitoring of the system air pressure at various locations to determine the pressure loss through the system.

22. Forty man-hours were required to drill the holes in the diffuser pipe, construct the control manifold, and install connectors on all of the pipes and hoses. Field installation of the system required about 140 man-hours including the onsite assembly, installation of the diffusers and supply hoses, and connection to the compressor. These figures do not include the construction of the compressor enclosure with a concrete floor or the work involved in supplying electricity to the building and compressor.

PART III: SYSTEM EVALUATION

23. The second objective of this investigation was an evaluation of how well the installed system performed under the field conditions at East Sidney Lake. As described earlier, the diffuser was fabricated to a length of 800 ft. During the 1989 (near-field) and 1990 (far-field) tests, because of pipe breakage, 600 ft of diffuser was operated with the maximum compressor output of 48 scfm. Tests are planned for subsequent years to determine system performance with other lengths of diffuser. The specific goals of the investigation reported herein were to (a) determine mechanical performance characteristics of the installed system and (b) determine the near-field and far-field effects of the destratification system on thermal structure in the lake. Tests to assess the near-field effects were conducted immediately after system installation in July 1989. Lake temperatures were monitored during the 1990 stratification season to determine the far-field effects of the system.

Compressor Evaluation

24. The first component in the evaluation of the system operation was the verification of the compressor discharge. The system design, discussed in Part II, indicated that airflow should be 54 scfm at a pressure of 48 psi. The compressor that was selected and installed was rated at 64 scfm at a pressure of 50 psi. To verify compressor capacity and measure airflow rate, an airflow meter (Model 1110, Tube No. B-13-H5G1A Brooks Rotameter) was installed to monitor the rate of airflow from the compressor under the existing pressure conditions. The meter was installed in the main air supply line in the compressor shed, just upstream of where the supply line turned down the face of the dam. The measured airflow was 48 scfm at a delivery pressure of 20.4 psi.

1989: Near-Field Effects

25. The investigation of the near-field effects of the destratification system consisted of monitoring the temperature profiles near the diffuser to determine the amount of mixing. Five stations were established on a line perpendicular to the diffuser (Figure 5). Stations B1, B2, B3, B4 and B5 were located 20, 50, 73, 141, and 216 ft away from the diffuser, respectively.

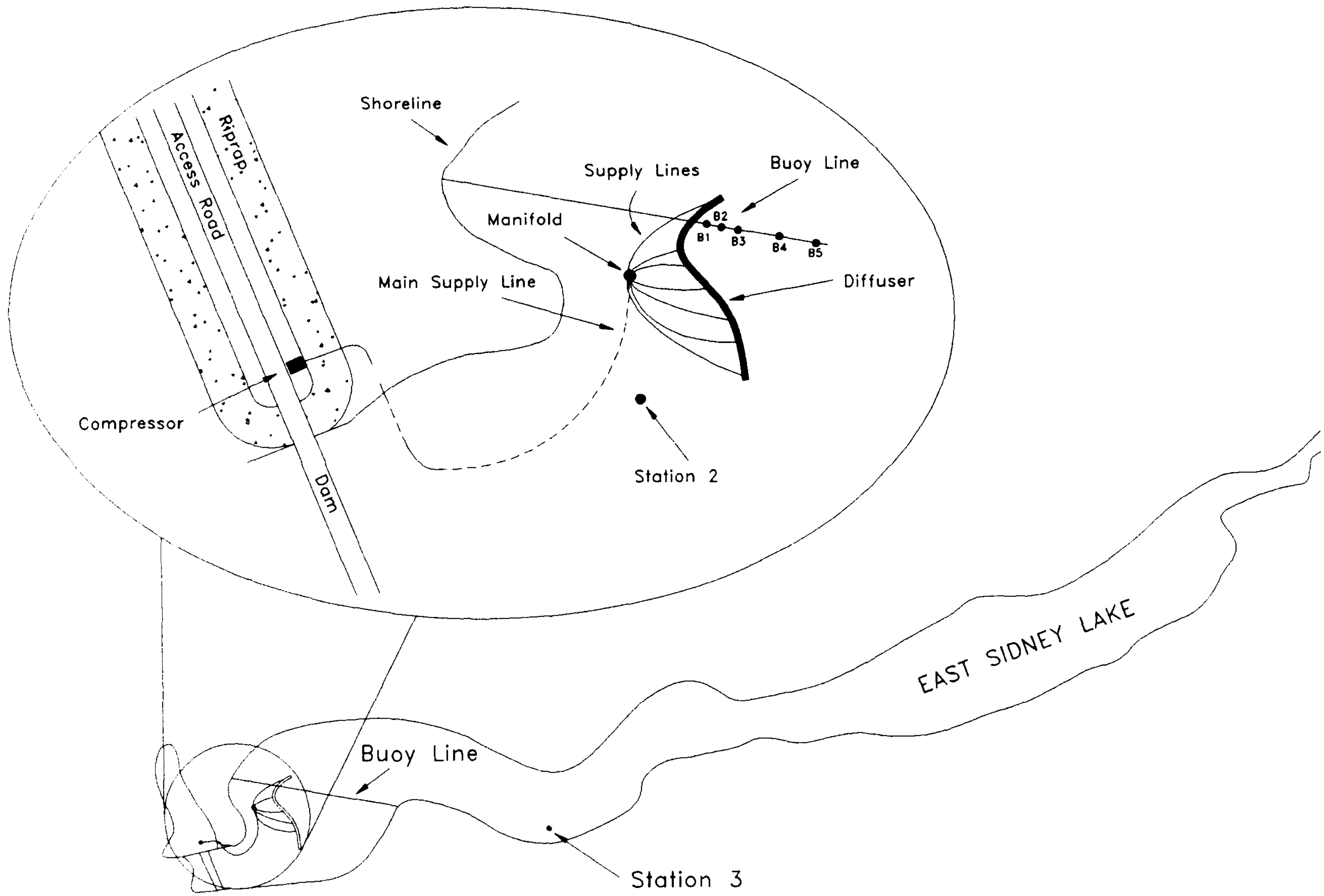


Figure 5. Schematic showing location of diffuser system and sampling stations

Temperature profiles were also monitored intermittently directly over the bubble plume. Thermistor chains that automatically recorded temperature profiles were installed at stations B1 and B2. Temperature and dissolved oxygen (DO) profiles were measured at the remaining stations using a YSI Model 58 temperature/DO meter. The system was configured during these tests with eight sections of diffuser in operation. The airflow was set at the compressor maximum of 48 scfm.

26. Several temperature profiles were recorded at station B1 prior to start-up of the destratification system to establish initial conditions. Figure 6 shows these profiles. Stratification in the hypolimnion was nearly linear ranging from about 19 °C at the bottom to nearly 21 °C at el 1137. In the metalimnetic region near the thermocline (elevation of maximum temperature change), the temperature gradient increased with the temperature ranging from 21 °C to about 25 or 26 °C at el 1144. The epilimnetic region extended from el 1144 to the surface with temperatures from about 25 °C to 26 or 27 °C. The total temperature difference from surface to bottom was approximately 7 °C. The objective of the destratification system is to mix hypolimnetic water with

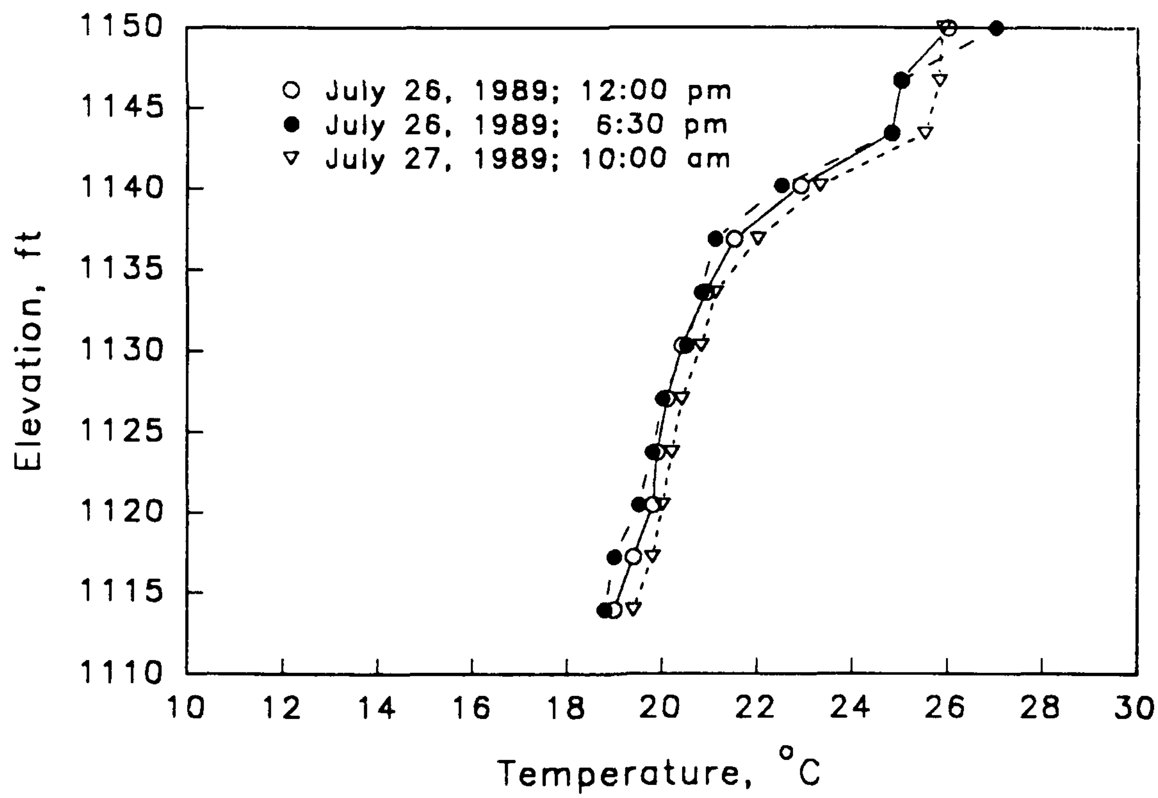


Figure 6. Temperature profiles at station B1 on 26 and 27 July 1989 (prior to system start-up)

epilimnetic water and thereby eliminate the strong thermal (and density) gradient in the vertical profile. The profiles in Figure 6 also show the diurnal heating and cooling near the surface.

27. The compressor was started at 10 a.m. on 27 July 1989 and operated until about 5 p.m. on 28 July. Temperature profiles that were collected directly over the diffuser showed a near-uniform profile of 21 °C from surface to bottom, indicating that the rising bubble plume was entraining and transporting hypolimnetic water to the surface.

28. Isothermal graphs, such as Figure 7, which were developed from profiles taken at station B1, show how the temperature of the water column changes over time. If the isotherms are very close together, the temperature gradient is strong; however, if the isotherms are far apart, the temperature gradient is slight. The isotherms in Figure 7 show that the initial temperature difference from surface to bottom was about 7 °C and that a strong temperature gradient (the metalimnetic region shown in Figure 6) extended from about el 1138 to 1144, but only slight stratification was present in the hypolimnetic region between el 1117 to 1138. The influence of the destratification process during the 36 hr of operation is clearly shown in Figure 7: (a) the temperature of the epilimnion decreased very quickly (in about 2-3 hr); (b) by 5 p.m. on 28 July, the temperature difference from bottom to surface had decreased to 4 °C; (c) the distance between the isotherms had increased dramatically; and (d) the strong thermal gradient in the metalimnetic region had been eliminated.

29. The mixing effect of the destratification system became less evident with distance from the diffuser. The profiles (Figure 8) collected at station B4, which was 141 ft from the diffuser, showed a trend similar to that observed at station B1; the isotherms gradually widened over time. The effects of the mixing at station B4 were not as immediate as at station B1, but after the 36 hr of operation, the temperature difference from bottom to surface had decreased from about 7 °C to about 4 °C. Extrapolating the rate at which destratification was occurring indicated that the design criteria of 2 °C should be met in the design period of 5 days.

1990: Far-Field Effects

30. The objective of this destratification system was to maintain a

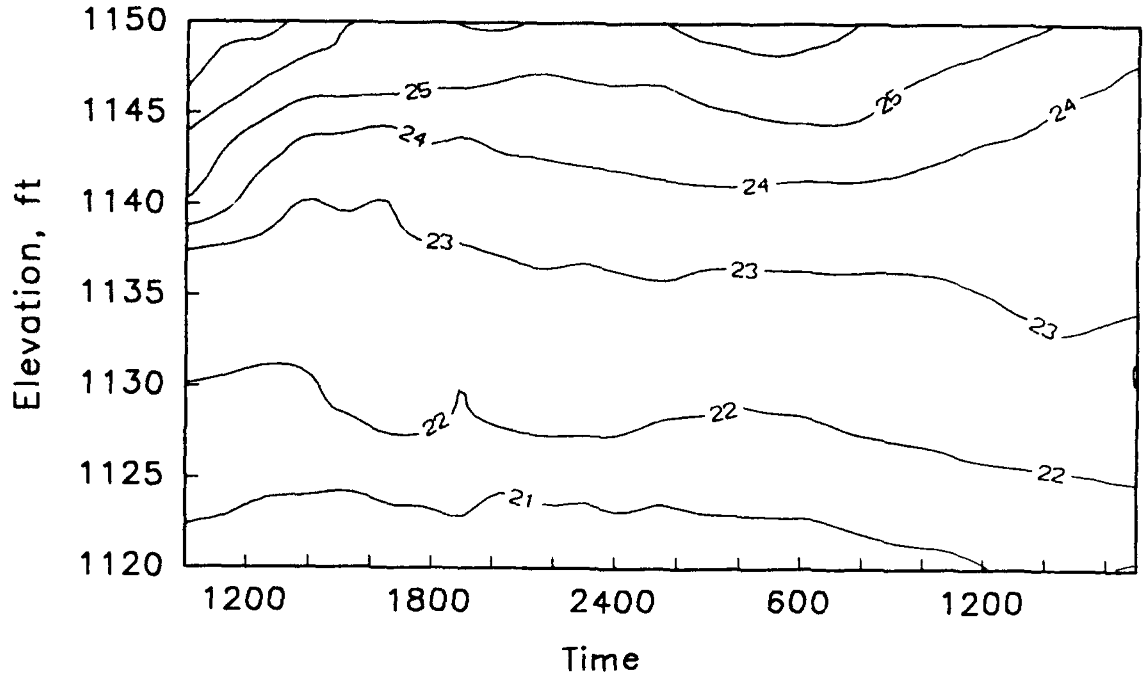


Figure 7. Isotherms showing temporal variations in the vertical distribution of water temperature at station B1 from 10 a.m. on 27 July to 5 p.m. on 28 July

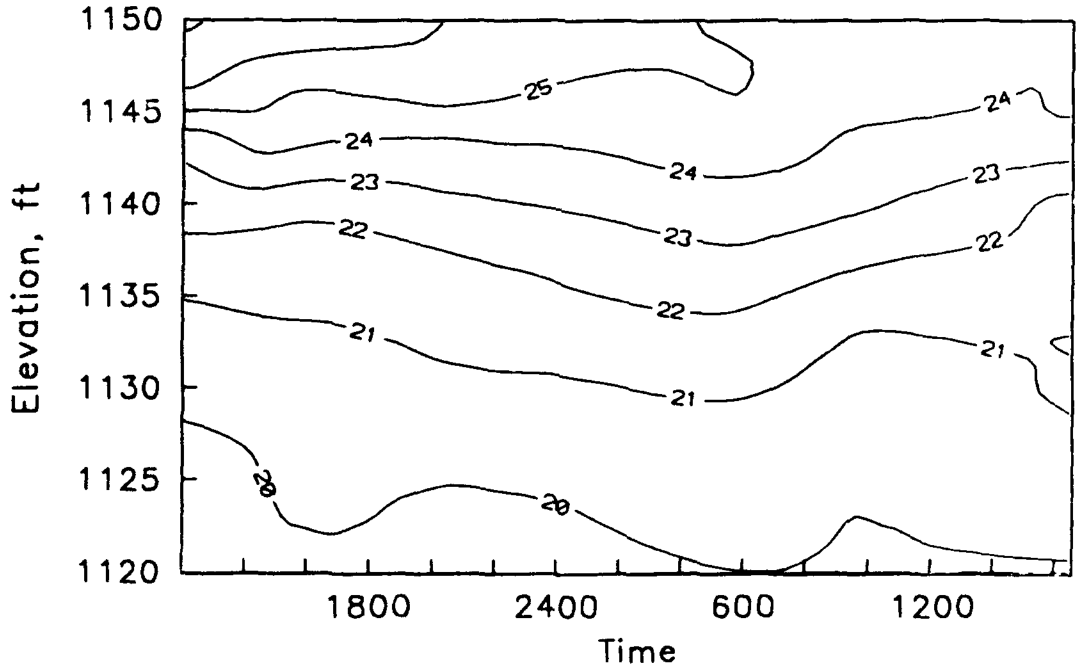


Figure 8. Isotherms showing temporal variations in the vertical distribution of water temperature at station B4 from 10 a.m. on 27 July to 5 p.m. on 28 July

2 °C temperature difference between the surface and the level of the diffuser. The effectiveness of the system at achieving this goal may be controlled by several factors. The length of the diffuser, the flow rate of air, and, particularly, the duration of compressor operation can be varied to modify the amount of energy which the system contributes to mixing the lake. After the initial destratification (to less than 2 °C top to bottom), the system should be able to maintain this temperature gradient for the remainder of the stratification season. For maximum operational efficiency, the compressor should operate only when necessary to compensate for surface heat input from solar radiation. However, this may require constant adjustments in the time of operation of the compressor.

31. The system was operated during the 1990 stratification season to determine the extent of full-lake destratification achieved by the system. The evaluation of far-field effects was based on observed temperature profiles throughout the lake. The system was considered successful if the temperature objective (less than 2 °C difference from top to bottom) was met within the specified destratification time (5 days). As mentioned, the system was configured during the 1989 and 1990 seasons with six sections of the diffuser in operation (because of pipe breakage). The stations established during the 1989 season were sampled on a variable schedule, depending on the operation of the destratification system and conditions in the lake. A YSI Model 58 meter was used to monitor the temperature and DO concentrations at the surface and at 3.3-ft intervals over the depth of the reservoir.

32. In addition to the regular stations, a thermistor chain was deployed at station 5, approximately 98.4 ft upstream of station 2 near the diffuser system (Figure 9). The chain was anchored so that fluctuations in the pool level would not affect the elevation of the individual thermistors. The first thermistor was located just below a submerged buoy at approximately el 1148. The remainder were spaced at 3.3-ft intervals to the bottom. The thermistor chain was programmed to collect and store hourly temperature profiles.

33. Since meteorological conditions are a major influence in the development of stratification, a weather station was installed on the compressor shed situated on the top of the dam. This station collected and stored air temperature, precipitation, relative humidity, and wind direction and speed.

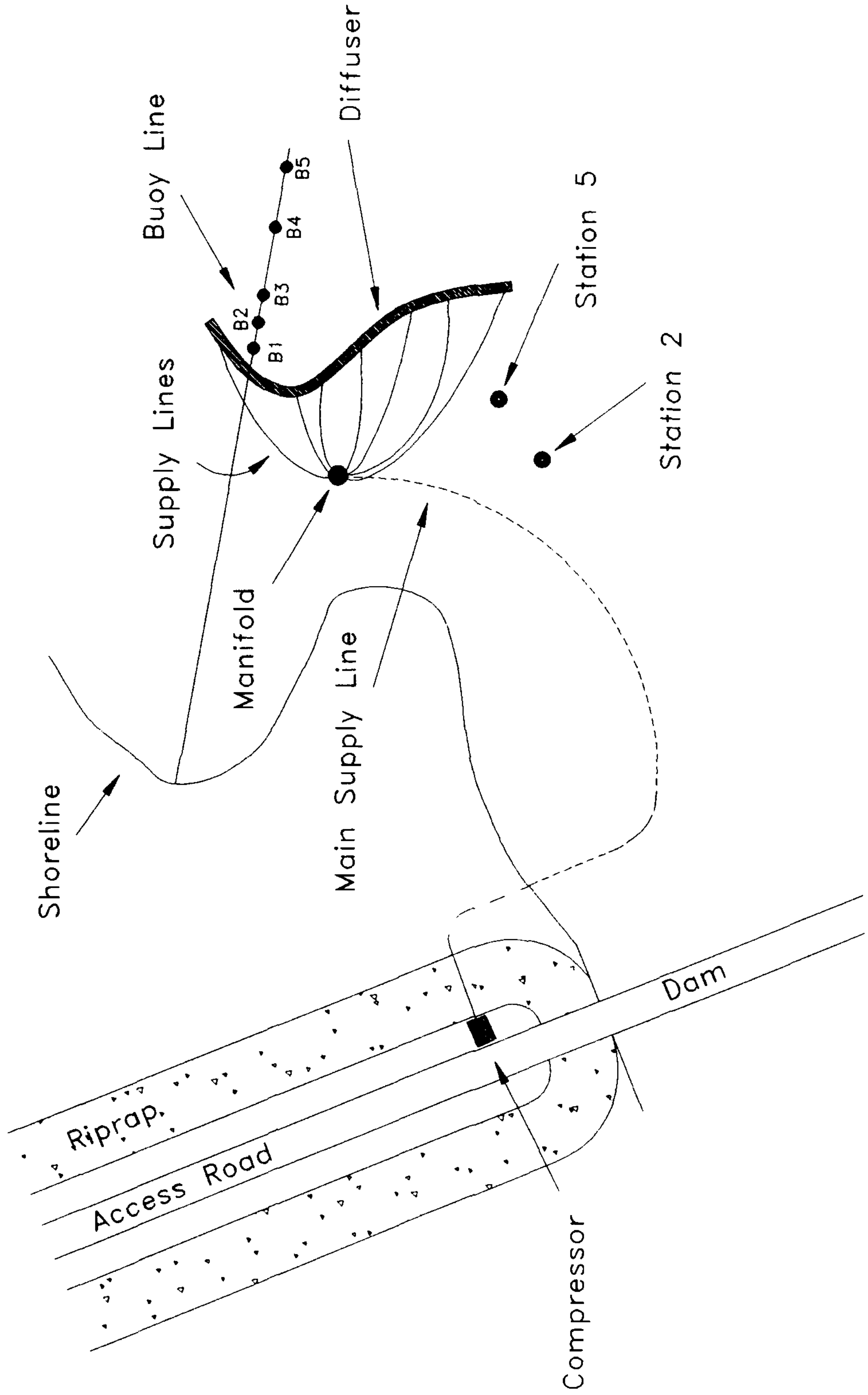


Figure 9. Station 5 location for 1990 stıdy

These parameters were sampled once every 10 sec, averaged, and stored every hour.

34. The operating schedule for 1990 is shown in Table 3. From 21 May through 14 June 1991, the system was operated for 23 hr/day to destratify the reservoir as completely as possible. As shown in succeeding sections, the system locally destratified the reservoir to within the design criteria of Davis (1980), i.e., 2 °C from top to bottom in 5 days. However, as will be discussed, at more remote stations, destratification was not as complete nor as rapid. After this initial period, the operation time was reduced to 12 hr/day to determine the minimum energy required to maintain the temperature gradient. Because of thermal input during July, the thermal stability began to increase, so operation time was increased to 18 hr/day. Toward the end of the summer the DO level in the lower reaches of the lake dropped to between 2 and 3 mg/ℓ. (Recall that low DO in the lower levels of the lake was the second criterion that would initiate the system operation.) In an effort to increase the DO in this region of the lake, the operating time of the system was increased to 23 hr/day on 5 September. The system was deactivated on 2 October 1990.

Table 3

Compressor Operation Schedule

Julian Date	Calendar Date	Compressor Operation, hr/day	Action On, hr	Action Off, hr
122	2 May 90	Thermistor chain installed		
124	4 May 90	Weather station installed		
141	21 May 90	23	2400	2300
166	15 Jun 90	12	0800	2000
207	26 Jul 90	18	0600	2400
248	5 Sep 90	23	0100	2400
275	2 Oct 90	Off		

35. Temperature profiles collected using the thermistor chain and YSI meter were analyzed to determine the overall effectiveness of the destratification system. Two criteria by which the system effectiveness can be evaluated are (a) the temperature difference between the surface water and the water at the level of the diffuser and (b) the stability of the reservoir based upon the temperature profile. Both of these criteria were taken into

account in the design of the system and should be good indicators of the overall effectiveness.

36. According to the design objectives specified by Davis (1980), by operating nearly continuously, the system should be able to maintain a 2 °C temperature difference from the surface to the level of the diffuser after the initial start-up, even with the highest thermal input. As shown in Figure 10, when the system was operated more than 18 hr/day, although at some instances the temperature difference was as great as 4.5 °C, generally, the temperature difference from el 1148 to 1115.2 at station 5 was less than 2-3 °C. At station 2, approximately 98 ft downstream of the diffuser system, the temperature difference between el 1147 and 1117 was often greater than the design maximum of 2 °C (Figure 11). The differences in temperatures between stations 2 and 5 are probably the result of incomplete mixing by the destratification system. As discussed in the next paragraph, the incomplete mixing may be the consequence of operating a modified design of the system (excess length of diffuser).

37. To evaluate the far-field or whole-lake effects, data from station 3 (Figure 5) were examined. Figure 12 compares the temperature differences between el 1146.7 (3 ft deep) and el 1130.3 (20 ft deep, bottom at station 3) for stations 2 and 3. As can be seen, the temperature differences demonstrate very similar responses to activation of the destratification system. In the first several days after activation of the destratification system, the surface-to-bottom temperature difference at station 3 was much larger than the difference at station 2. This apparent delay in effect is the result of the time required for mixing to materially affect the temperature profile at station 3. As the system operated through the summer, the temperature differences between depths of 3 ft and 20 ft declined at stations 2 and 3. However, the temperature difference at station 3 was consistently greater, by 1 or 2 °C, than the temperature difference at station 2. Although relatively small, this lack of destratification is probably the result of (a) operating a modified design of the destratification system or (b) an effect of reservoir bathymetry that is not included in Davis' (1980) design considerations.

38. Isothermal plots of water temperature (Figure 13) show an alternative view of the effects of destratification. In the week prior to system activation, the isotherm plot clearly shows the onset of stratification; i.e., the isotherms are sloped, indicating a relatively large temperature difference

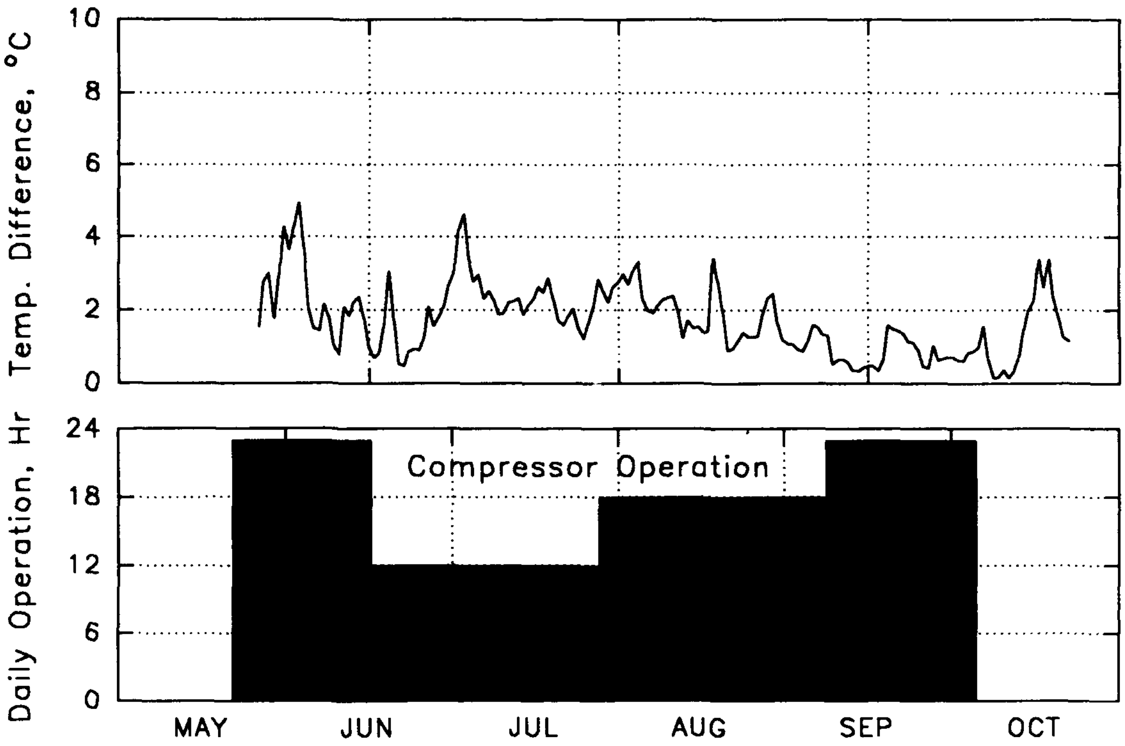


Figure 10. Temperature difference between el 1147 and 1117 at station 5 (thermistor chain)

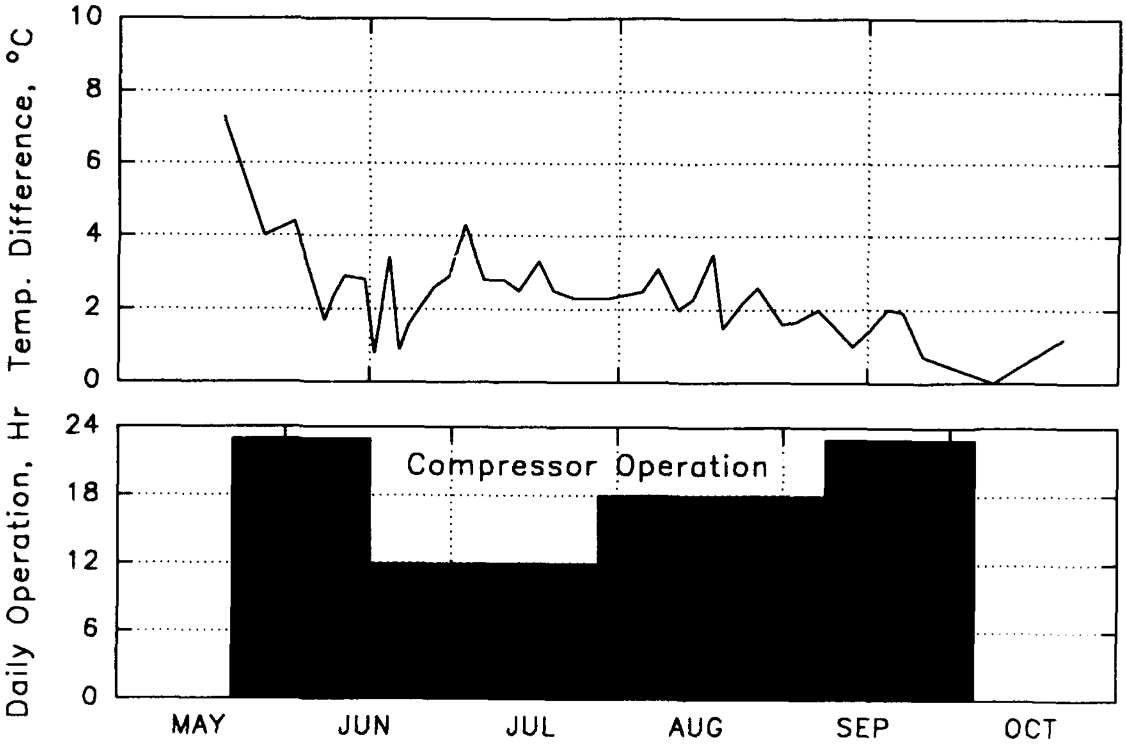


Figure 11. Temperature difference between el 1147 and 1117 at station 2

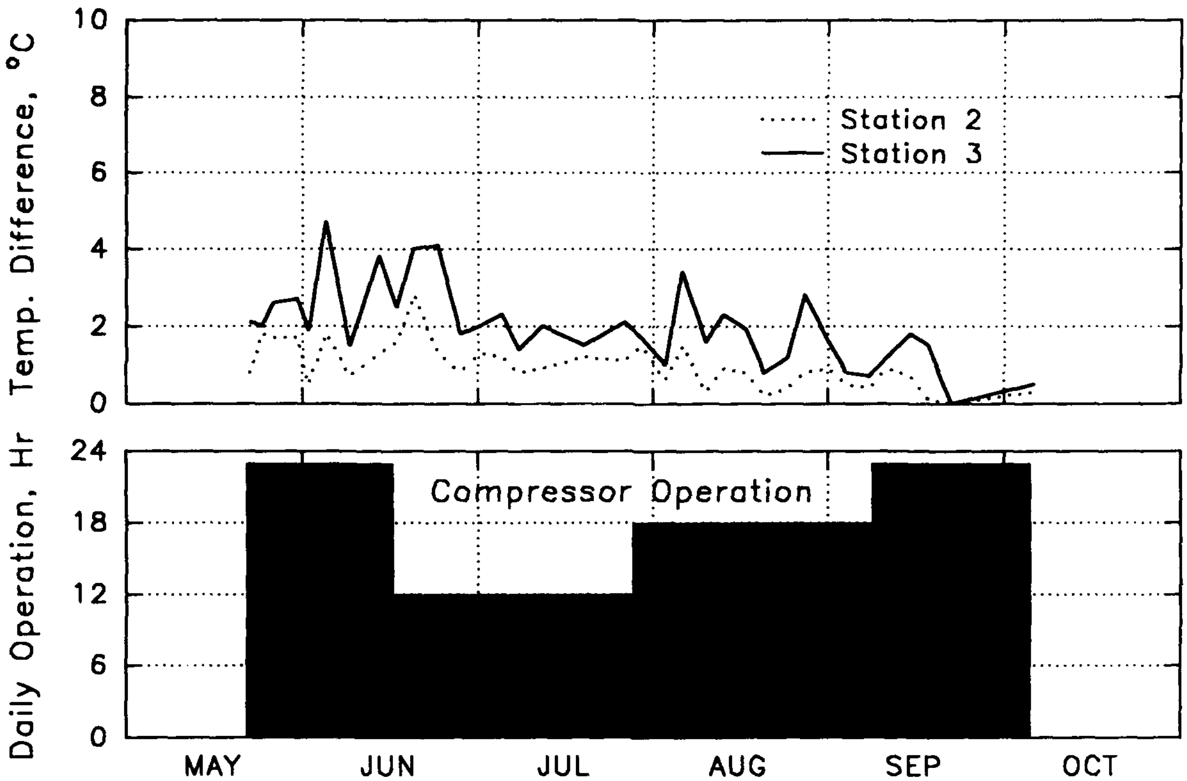
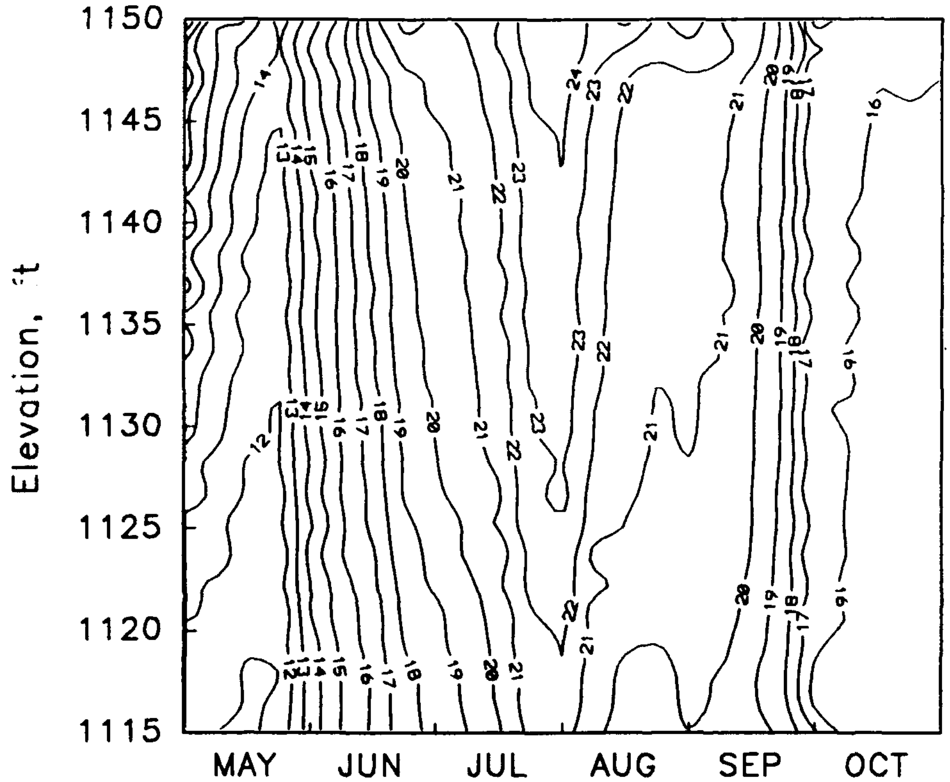


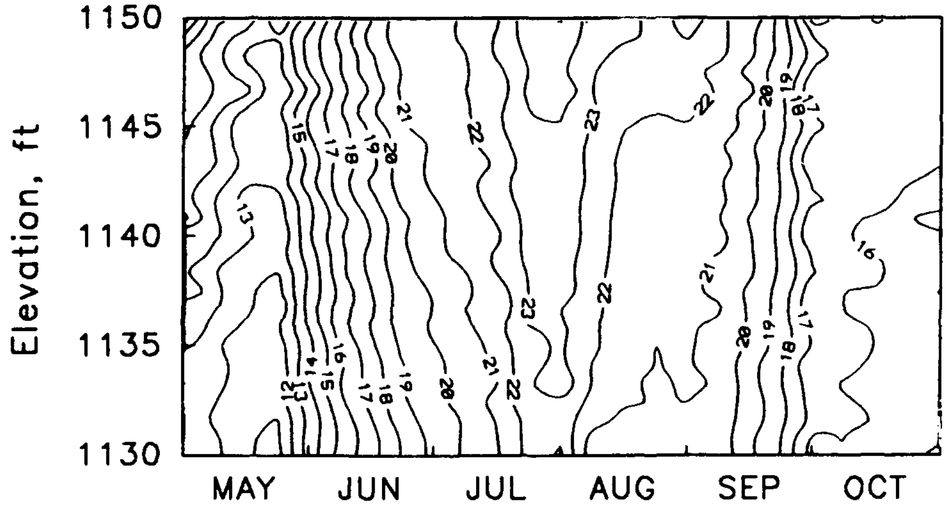
Figure 12. Temperature difference between depths of 3 ft and 20 ft for stations 2 and 3

from surface to bottom. When the compressor operation began on 21 May 1990 (Day 141), the isotherms quickly became more vertical as the reservoir was mixed, indicating reduced stratification. During the period of minimal system operation (12 hr/day from 15 June to 26 July, Day 166 to Day 207), occasional levels of stratification are indicated by the isotherms that are nonvertical. However, as discussed in the previous paragraph, the temperature difference between depths of 3 ft and 20 ft was usually less than 2 °C.

39. The second criterion used to gage the efficiency of the system was the change in the stability of the reservoir. The stability was computed according to the procedures described by Davis (1980). The temperature profiles observed at station 2 were used for this calculation. Figure 14 shows the stability in relation to the operation of the destratification system. Although not impossible, it is difficult to discern relationships between parameters shown in Figure 14. However, if the stability, solar radiation, and precipitation data are averaged (moving-average) over a 3-day period, the day of interest and 2 days prior, the extreme daily variation is dampened (Figure 15). The stability was affected most when the compressor was operated



a. Station 2



b. Station 3

Figure 13. Isothermal plots of water temperature over time for stations 2 and 3

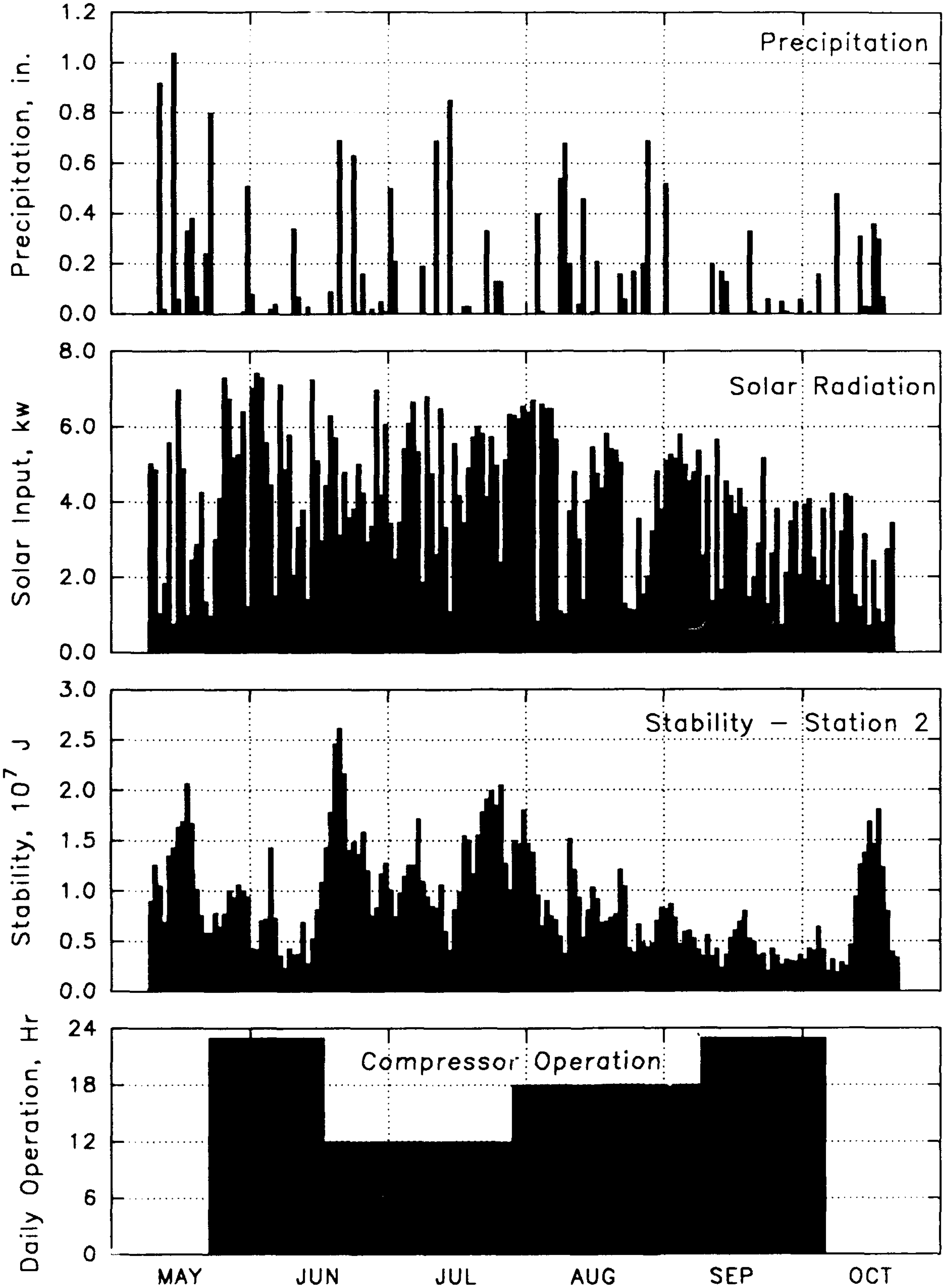


Figure 14. Stability, solar radiation, precipitation, and system operation verses time

Figure 14. Stability, solar radiation, precipitation, and system operation verses time

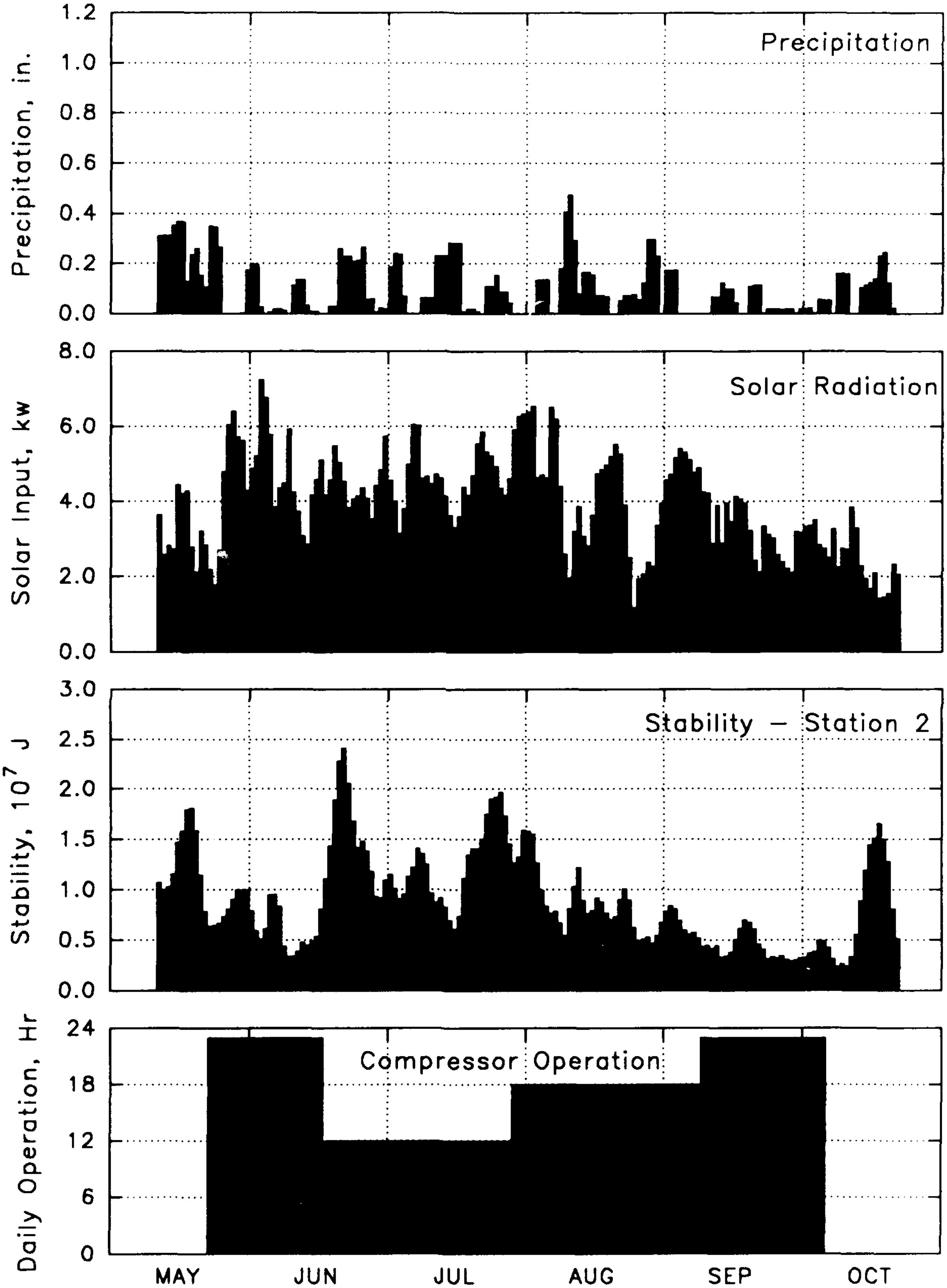


Figure 15. Three-day moving average of precipitation, solar radiation, and stability

for more than 18 hr/day. Increases in stability corresponded well with periods of high solar radiation; however, the magnitude of increase was far less and of shorter duration when the system operated in excess of 18 hr/day compared to the 12-hr/day operation. During the time when the system was reduced to operating 12 hr/day, the thermal stratification increased, and thus the stability increased. When the system operation was increased to 18 hr/day, the stability dropped and remained significantly lower. Although precipitation would only slightly impact stability directly (rainfall on the reservoir's surface), inflow as a result of precipitation could significantly and rapidly alter stratification. From this perspective, precipitation in significant amounts tended to decrease the stability.

40. The operation of the system during the 1990 season was based primarily on temperature profiles. However, the levels of DO were also closely monitored. Figure 16 shows isopleths of DO concentration verses time for station 2. In early September, the DO concentration near the bottom of the reservoir fell below 3.0 mg/ℓ and was apparently approaching the critical design DO level of 2.0 mg/ℓ. Consequently, the operating time of the destratification system was increased from 18 hr/day to 23 hr/day to increase the mixing and raise the DO concentration in the lower elevations of the reservoir. This increase in daily operation appeared to be successful in improving DO levels near the lake bottom: the DO increased and did not fall below 3.0 mg/ℓ for the duration of the 1990 tests.

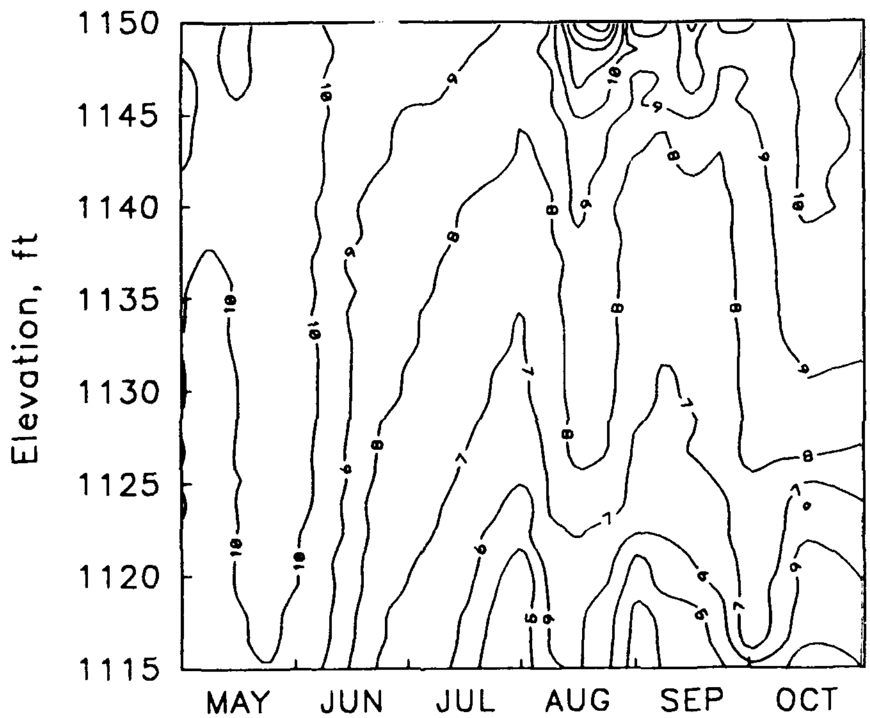


Figure 16. Isopleths of DO at station 2 over time

PART IV: SYSTEM OPERATION

41. The final objective of this investigation was the development of operational guidance for the destratification system. This procedure consisted of monitoring the thermal stratification and developing a protocol for establishing an appropriate compressor operation schedule.

Monitoring Thermistors

42. To develop a routine monitoring capability and a protocol for operation of the destratification system, two single thermistors were deployed off the face of the dam. One was located at approximately el 1149 (ordinarily 1.0 ft beneath the normal pool elevation), while the other was located at el 1128 (about 22 ft below normal pool). Data from these two thermistors were recorded on an hourly basis for retrieval via satellite communication. Once synchronized with temperature readings at other locations, the temperatures monitored with these thermistors would be used as key parameters that determine when and for how long the destratification system should be operated.

43. To evaluate these thermistors for monitoring the destratification processes, the temperatures observed at the dam face were compared to the temperatures observed with the thermistor chain at station 5 near the diffuser. The temperature differences between the two thermistors on the dam and the differences between the thermistors at station 5 (on the thermistor chain near the diffuser) at el 1148.7 and 1125.7 (the approximate elevations of those on the dam face) showed the same trends (Figure 17). When the compressor was operated for more than 18 hr/day, the temperature difference at the dam face or at station 5 from approximately el 1148 to el 1126 was generally less than 2 °C. The temperature difference at the dam face appeared to be slightly greater than that found at the thermistor chain. Since the dam is located approximately 650 ft downstream from the thermistor chain, the destratification system was less effective at mixing; consequently, the temperature gradient was greater. Similar effects were observed at station 3 near the inflow to the lake.

44. In summary, the thermistors located on the dam appear to be an acceptable reflection of the temperature differences in the reservoir. Consequently, observations from these thermistors can be used as key parameters for

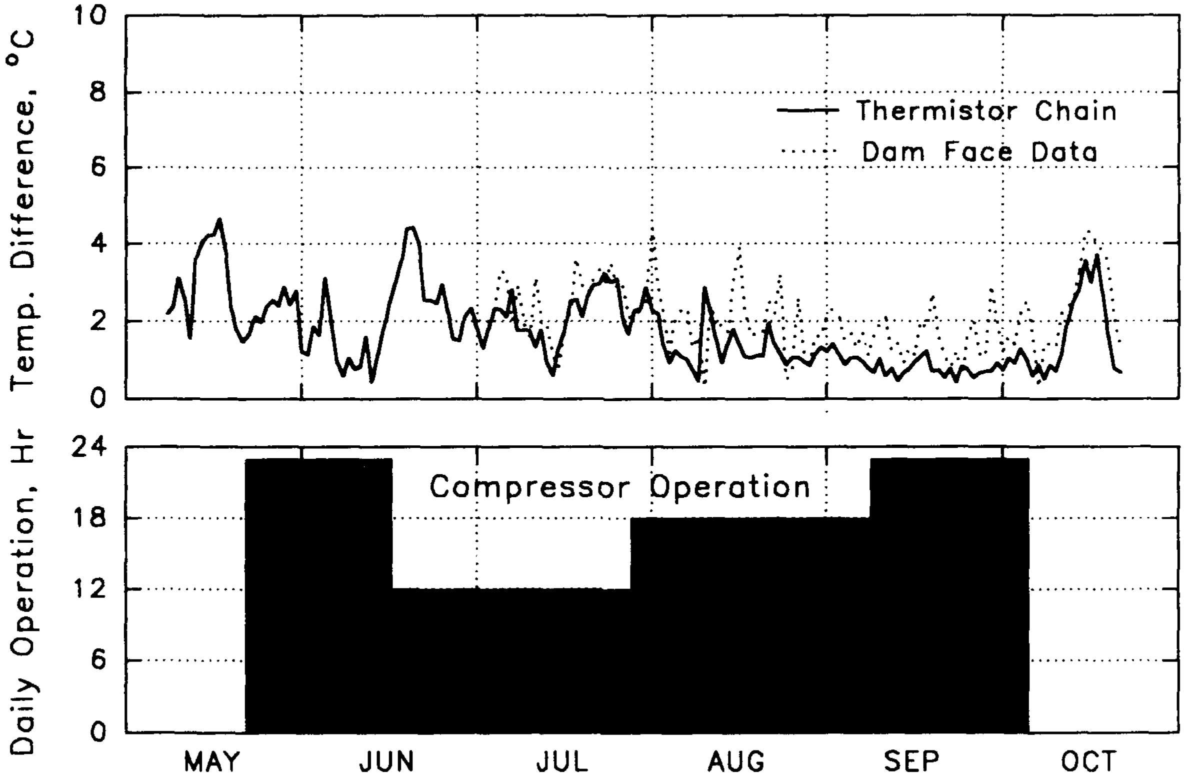


Figure 17. Temperature differences between el 1148 and 1128 for station 5 and dam face

controlling the operation of the destratification system. If the difference at the dam is consistently greater than 3 °C, then the daily operational time of the system should be increased. If it is usually less than 3 °C, the operating time of the system should be reduced.

System Operation Schedule

45. Based on the 1989 and 1990 observations, the destratification system should be activated sometime between the middle of May and the beginning of June. This is the approximate time that the lake develops a 4 °C temperature gradient top to bottom. These dates are only approximate and could shift 2 to 3 weeks depending upon meteorological conditions. A more accurate and timely indication of when to start the destratification system would be the temperature difference measured by the thermistors mounted on the face of the dam.

46. Once operation has commenced, the system should be operated at the maximum daily duration (23 hr/day) for 10 to 14 days or until the operational

protocol discussed in the previous section has been met. From the data collected during the 1990 season, for the design in operation, it would appear that the minimum daily operating time is between 12 and 18 hr per day. The system can probably be deactivated in mid-September when the lake becomes completely mixed.

Secondary Impacts of System Operation

47. The operation of a destratification system using a compressor such as this system may create secondary impacts associated with its operation. The 15-hp electric motor on the compressor generates considerable noise, even when the doors of the compressor building are closed, creating a concern for disturbance of campers near the dam. However, during this testing period, no complaints were received from the campgrounds.

48. Concern was voiced that the diffuser could potentially increase the turbidity of the reservoir, because the currents set up in the vicinity of the diffuser may entrain bottom sediments and transport sediment particles into the water column. The potential for this occurrence was particularly strong during the initial start-up of the system at the beginning of each stratification season. However, although not quantified, only a slight increase in turbidity was observed in the vicinity of the bubble column.

System Maintenance

49. The compressor should be maintained according to the manufacturer's recommendations; however, the schedule may have to be modified to account for the prolonged operation of the compressor. The type of compressor initially selected for this system was designed to be used with an air tank so that the compressor does not operate continuously. In this particular application, however, the compressor operated 100 percent of the time. If the existing compressor is to remain in operation, to minimize wear and tear on the compressor, the feasibility of an air storage tank integrated into the air supply line should be investigated. As an alternative, the existing compressor could be replaced with one designed for continuous operation. For either case, the installation of a pressure and flow regulator would smooth compressor operation and thereby extend the life of the compressor.

50. According to Davis (1980), the system should be operated at least once a month during the off season. This is to prevent the accumulation of biological growth or sediment deposits in the holes of the diffuser, causing clogging of the air holes.

51. One final concern that may impact the operation of the system is the efficiency of the compressor under hot weather conditions. Since the compressor is housed in a small shed on top of the dam, the temperatures within the shed could become extremely high, especially during the late summer. Although the shed is ventilated, the ventilation may need to be increased. The temperatures in the shed should therefore be monitored.

PART V: CONCLUSIONS AND RECOMMENDATIONS

52. Many reservoirs maintained by the US Army Corps of Engineers are similar to East Sidney Lake. In general, the water quality is high; however, during summer stratification periods, algae blooms occasionally occur that impair recreational usage. Destratification is one technique that can be used to inhibit internal cycling of nutrients to prevent or minimize these algae blooms. Since the purposes of this study were rooted in applied research and solving a site-specific problem, the lessons learned are both general and site-specific. The initial design, discussed in the next paragraph, was modified to provide a large degree of flexibility in operation. This flexibility was included to permit evaluation of alternative operations in subsequent research studies. The initial configuration of the destratification system, which is the subject of this report, consisted of a diffuser longer than required by Davis' (1980) design criteria. Shorter lengths of diffuser should be evaluated relative to far-field effects. This would more closely validate Davis' design guidance. If operation of shorter length diffusers does not result in more complete mixing in the far field, then Davis' design procedure should be modified to better suit the long and narrow shape of reservoirs as compared to the round shape of natural lakes.

53. To gain general experience in the design, construction, and installation of a pneumatic destratification system, Davis' (1980) methodology, based on thermal stability of the lake, was used to design a system. The design required a minimum diffuser length of approximately 350 ft with a total airflow rate of 54 scfm. The diffuser was constructed of polyvinyl chloride (PVC) pipe, perforated with 0.0394-in.-diameter holes and weighted with bricks. Eight 100-ft-long diffuser segments were installed to provide a large degree of flexibility in diffuser length for testing. Air was supplied from an onshore compressor through a high-pressure hose to a PVC manifold, where airflow to each diffuser segment was controlled. For the tests conducted in 1989 and 1990 and reported herein, the system consisted of a diffuser length of 600 ft, fed with the maximum airflow rate of 48 scfm.

54. Pipe breakage appeared to be the most common problem associated with the diffuser system. In fact, pipe breakage between the 1989 and 1990 stratification season caused the loss of 200 ft of diffuser. During the 1991 stratification seasons, pipe breakage rendered all but one section of diffuser

inoperable. For this type of system to be generally attractive, a method for effective diffuser maintenance must be developed. Alternative materials, from which the system is fabricated, may reduce the occurrence of this problem, and should therefore be investigated.

55. The type of compressor initially installed at East Sidney required a rigorous maintenance schedule to assure reliable operation. For future design or a replacement compressor at East Sidney, a compressor designed for continuous operation should be considered. Flowmetering and pressure control devices should also be installed to aid in system operation.

56. To evaluate system performance and determine the adequacy of the design methods, in-lake temperature and dissolved oxygen (DO) measurements were made in 1989 and 1990. Near-field tests and far-field tests were conducted in 1989 and 1990, respectively. Initial tests of near-field conditions in 1989 indicated that the rising bubble plume from the diffuser entrained hypolimnetic water and transported it to the surface. The effects of entrainment and the resulting mixing were clearly identifiable in observed temperature profiles, where the maximum temperature difference from surface to bottom decreased significantly. In the near field, the installed system caused sufficient mixing to essentially meet the design criteria of a maximum residual stratification of 2 °C from surface to bottom within the design period of 5 days.

57. Temperature profiles collected to evaluate the far-field effects of the system, or whole-lake destratification, indicated that the system significantly influenced the far-field temperature profiles. However, the surface-to-bottom temperature differences in the far field were greater than those observed near the mixing action of the diffuser. For station 3, the most remote from the diffuser system, the temperature difference was slightly greater than the design standard of 2 °C from surface to bottom. Although seemingly small, this lack of destratification may be the result of (a) the bathymetry of a reservoir verses a natural lake (for which Davis (1980) developed the design criteria), or (b) operating a 600-ft-long diffuser with 48-scfm airflow, rather than the design length of 350 ft with 54-scfm airflow. Underloading the diffuser (compared to Davis' design criteria) may restrict the destratification capability.

58. In addition to surface-to-bottom temperature differences, the stability of the lake was also used in evaluating the effectiveness of the

destratification system. During periods when the system was operating, the stability of the lake was decreased. During periods of high solar input to the lake, the stability increased; but when the system was operating for more than 18 hr/day, the peaks in stability were significantly attenuated. Inflow to the lake from storm events appeared to decrease lake stability. Thus, rainfall, which was monitored at a local weather station, was found to correlate with decreased lake stability.

59. Although temperature differences or lake stability was used to measure the success of the destratification effort, the system could also increase the DO in the lower regions of the reservoir. In early September 1990, although the system appeared to be maintaining the desired temperature gradient, the level of DO in the lower elevations dropped below 3 mg/ℓ. The time of compressor operation was increased from 18 to 23 hr/day with a resulting improvement in the hypolimnetic DO.

60. To develop an operational protocol, two thermistors were deployed off the dam face at approximately el 1148 and 1128. Comparison of the temperature differences between these two thermistors and the temperature differences at other locations indicated that the thermistors located on the dam face could be used to monitor the destratification process and to schedule operation of the compressor. In general, the compressor should begin operation in mid-May to late May and may be deactivated in late September, depending on the stratification.

REFERENCES

Asaeda, T., and Imberger, J. 1988. "Structures of Bubble Plumes in Stratified Environments," Environmental Dynamics Report ED-88-250, Center for Water Research, University of Western Australia, Nedlands, Western Australia.

Davis, J. M. 1980 (Aug). "Destratification of Reservoirs - A Design Approach for Perforated Pipe Compressed Air Systems," Water Services, pp 497-504.

Gossens, L. 1979. Reservoir Destratification with Bubble Column, Delft University Press, Delft, The Netherlands.

Johnson, P. L. 1984. "Thoughts on Selection and Design of Reservoir Aeration Devices," Lake and Reservoir Management, Proceedings of the Third Annual Conference, North American Lake Management Society, 18-20 October 1983, Knoxville, TN, US Environmental Protection Agency, Washington, DC, pp 537-541.

Karanenburg, C. 1979. "Destratification of Lakes Using Bubble Columns," Journal of Hydraulics Division, ASCE, Vol 105, No. HY4, pp 333-349.

Kennedy, Robert H., Ashby, Steven L., Gaugush, Robert F., and Gunkel, Robert C., Jr. 1988. "Eutrophication Assessment and Management at Tioga, Hammond, Cowanesque, Whitney Point and East Sidney Lakes, Pennsylvania - New York," Miscellaneous Paper EL-88-6, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Meyer, E. B. 1991 (March). "Pneumatic Destratification System Design Using a Spreadsheet Program," WOTS Information Exchange Bulletin, Vol E-91-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Patterson, J. C., and Imberger, J. 1989. "Simulation of Bubble Plume Destratification Systems in Reservoirs," Aquatic Sciences, Vol 51, No. 1, pp 3-18.

Symons, J. M., ed. 1969. "Water Quality Behavior in Reservoirs; A Compilation of Published Research Papers," Consumer Protection and Environmental Health Service, Bureau of Water Hygiene, Cincinnati, OH, for sale by US Government Printing Office, Washington, DC.

Zic, K., and Stefan, H. G. 1990. "Lake/Reservoir Destratification Induced by Bubble Plumes," Project Report No. 313, Prepared by St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN, for US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Zic, K., Stefan, H. G., and Ellis, C. "Laboratory Study of Bubble Plume Destratification," Submitted to Journal of Hydraulic Research, IAHR.

Waterways Experiment Station Cataloging-in-Publication Data

Meyer, Edward B.
Destratification system design for East Sidney Lake, New York / by Edward B. Meyer, Richard E. Price, Steven C. Wilhelms ; prepared for Department of the Army, U.S. Army Corps of Engineers ; monitored by Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station.
43 p. : ill. ; 28 cm. — (Miscellaneous paper ; W-92-2)
Includes bibliographical references.
1. Reservoirs — New York (State) — Sidney — Destratification. 2. East Sidney Lake (N.Y.) 3. Water quality management — New York (State) — Sidney. 4. Lake renewal — New York (State) — Sidney. I. Price, Richard E. II. Wilhelms, Steven C. III. United States. Army. Corps of Engineers. IV. U.S. Army Engineer Waterways Experiment Station. V. Water Quality Research Program. VI. Title. VII. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; W-92-2.
TA7 W34m no.W-92-2